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Shallow Stormwater Infiltration Devices vs. Injection Well Systems: a Comparison of Groundwater Contamination Potential

I. Introduction

While the water-sequestering function of soils has long been recognized for its use in mitigating excess stormwater runoff, in some quarters there has been a lack of confidence by regulatory agencies in the use of roadside swales and shallow infiltration devices to remove pollutants from stormwater before it enters the subsurface water table. This bulletin provides an overview of recent research on the efficacy of roadside and bioretention swales and shallow infiltration devices (e.g. pervious pavements, crushed stone pads over undisturbed soils, and rain gardens) for their removal of common urban stormwater pollutants and the subsequent quality of stormwater-recharged groundwater sources, as well as a comparison to subsurface injection wells for groundwater contamination potential.

II. Overview of Urban Stormwater Pollutants and Their Contamination Potentials

Figure 13-1 - Roadways and parking lots are common places for pollutants such as petroleum and heavy metals to be introduced into stormwater (source: Booth 1999)

In recent decades, recognition of the environmental and financial costs of traditional stormwater management has led to the creation of best management practices that encourage infiltration of excess urban stormwater into the soil. However, this stormwater accumulates a variety of pollutants (see table 13-1 and figure 13-1) as it flows over the urban landscape, which has led to questions about the capacity of soils to filter these quantities of polluted stormwater effectively and to prevent contaminants from entering groundwater sources. Stormwater runoff enters groundwater in three ways[1]:

1. surface infiltration into soil (e.g. grass swales without pretreatment)
2. sedimentation or filtration prior to infiltration into soils
3. subsurface injection

Table 13-1 - Non-Point Urban Stormwater Pollutants and Their Sources

Non-point urban stormwater pollutants	Pollutant	Common sources
Sediments	Particulates	Atmosphere, erosion, vehicle wear
Nutrients	Nitrogen	Atmosphere, fertilizers, detergents
	Phosphorous	
Heavy Metals	Zinc, lead, iron	Fungicides, insecticides, tire wear, motor oil, engine parts, rust, machinery
	Copper, cadmium, chromium	
	Nickel, manganese, cyanide	
Hydrocarbons	Petroleum	Spills, leaks, antifreeze, hydraulic fluids, asphalt surface leachate
Organic Compounds	Phthalate esters, phenolic compounds, and volatile organics	Pesticides, plastics, cleaners
Microorganisms	Bacteria	Combined sewer overflows and illicit connections
	Viruses	
Salts	Sodium and chlorides	Road de-icing salts

adapted from Pitt et al, 1994; EPA, 1993[2]

These pollutants' potential to contaminate groundwater depends on a variety of factors[3]. Toxin mobility and solubility vary; heavy metals are generally less mobile in soils but can be moderately or highly mobile in water that is injected subsurface, while nitrate and some organics are highly soluble and stay in solution in percolation water. In particular, if nitrate is not taken up by plants before it filters through the root zone, it has high potential to contaminate groundwater. While most bacteria are large enough to be trapped by soil particles, viruses are very small and often move easily through soils.

Soil texture and depth are also factors. Sandy soils and soils with low organic matter content allow greater mobility of toxins, but greater soil depths for most soils will decrease contamination potential. Clearly, water tables that are near the surface will be more susceptible to contamination. Some pesticides can decompose in the soil, and some organics can be removed from the soil and runoff by volatization and degradation.

Research by the US Environmental Protection Agency[4,5] has shown that the risks for groundwater contamination are significantly higher with subsurface injection than with surface infiltration, whether treated or untreated (see table 13-2). The pollutants that pose the highest risk for groundwater contamination through surface infiltration are chloride, especially in areas where they are applied as de-icers[6], and enteroviruses, which can be problematic in areas with combined sewer overflows. While these pollutants are equally persistent in treated and injected stormwater, it is significantly less favourable to introduce them purposely and directly into groundwater sources. The research also found that, for residential runoff, surface infiltration and soil percolation is particularly effective in removing heavy metals and organic compounds such as 1,3 dichlorobenzene, pyrene and fluoranthene, many of which pose high contamination risks when injected subsurface. Runoff from manufacturing industrial areas, snowmelt, construction sites, and vehicle service facilities, dry weather storm drainage effluent, and combined sewage overflows should be diverted from infiltration devices and should never be injected subsurface due to higher concentrations of soluble toxicants, soluble salts, pathogens, and suspended solids.

Table 13-2 - Potential of Stormwater Pollutants to Contaminate Groundwater

Compounds		Mobility (sandy/low organic soils)	Abundance in Stormwater	Fraction Filterable	Contamination Potential: Surface Infilt. and No Pretreatment	Contamination Potential: Surface Infilt. with Sedimentation	Contamination Potential: Sub-surface Inj. with Minimal Pretreatment
Nutrients	nitrates	mobile	low/moderate	high	low/moderate	low/moderate	low/moderate
Pesticides	2,4-D	mobile	low	likely low	low	low	low
	γ-BHC (lindane)	intermediate	moderate	likely low	moderate	low	moderate
	malathion	mobile	low	likely low	low	low	low
	atrazine	mobile	low	likely low	low	low	low
	chlordane	intermediate	moderate	very low	moderate	low	moderate
	diazinon	mobile	low	likely low	low	low	low
Other organics	VOCs	mobile	low	very high	low	low	low
	1,3-dichloro-benzene	low	high	high	low	low	high
	anthracene	intermediate	low	moderate	low	low	low
	benzo(a) anthracene	intermediate	moderate	very low	moderate	low	moderate
	bis (2-ethylhexyl) phthalate	intermediate	moderate	likely low	moderate	low	moderate
	butyl benzyl phthalate	low	low/moderate	moderate	low	low	low/moderate
	fluoranthene	intermediate	high	high	moderate	moderate	high
	fluorene	intermediate	low	likely low	low	low	low
	naphthalene	low/inter.	low	moderate	low	low	low
	pentachlorophenol	intermediate	moderate	likely low	moderate	low	moderate
	phenanthrene	intermediate	moderate	very low	moderate	low	moderate
	pyrene	intermediate	high	high	moderate	moderate	high
Pathogens	enteroviruses	mobile	likely present	high	high	high	high
	Shigella	low/inter.	likely present	moderate	low/moderate	low/moderate	high
	Pseudomonas aeruginosa	low/inter.	very high	moderate	low/moderate	low/moderate	high
	protozoa	low/inter.	likely present	moderate	low/moderate	low/moderate	high
Heavy metals	nickel	low	high	low	low	low	high
	cadmium	low	low	moderate	low	low	low
	chromium	inter./very low	moderate	very low	low/moderate	low	moderate
	lead	very low	moderate	very low	low	low	moderate
	zinc	low/very low	high	high	low	low	high
Salts	chloride	mobile	seasonally high	high	high	high	high

source: Pitt, Clark, and Parmer 1994

III. Bioretention Swales and Vegetated Buffers

Figure 13-2 - Parking lot bioretention installation, Greenbelt, Maryland (source: A. P. Davis)

Bioretention is a best management practice that uses porous soil, hardwood mulch, crushed stone pads over native soils, and plants to create landscaped basins that capture, hold, and filter stormwater from small paved areas (see figure 13-2). Many of the studies that once raised questions about the reliability and consistency of swales and buffers in removing stormwater pollutants were found to be poorly designed[7] and have recently been replaced by more rigorous field and laboratory studies, such as those undertaken at the University of Maryland to quantify the effectiveness of bioretention methods in removing stormwater pollutants.
Both lab and field studies found that bioretention facilities were particularly effective at removing heavy metals from stormwater, significantly reducing the concentrations of copper (Cu), lead (Pb), and zinc (Zn). Moderate reductions of total kjeldahl nitrogen (TKN), ammonium ($NH4+$), and phosphorus (P) levels were found; however, little nitrate ($NO3-$) was removed from the stormwater as it filtered through the soil[8]. Further studies found that while increased soil depth increased the removal of heavy metals, variations in stormwater runoff pH, duration, intensity, and pollutant concentrations had minimal effect on the removal of these heavy metals through the bioretention system[9].

Several studies have found that vegetated medians and shoulders with moderate slopes along roads and highways can effectively reduce pollutant loads in stormwater runoff. Like bioretention systems, these areas provide the vegetation and soil necessary for the filtration, sedimentation, adsorption, and biological and chemical activity that cleanses stormwater. For example, a two-year water quality monitoring project conducted over eight sites across California tested the effectiveness of existing vegetated slopes adjacent to freeways in removing stormwater contaminants[10]. The study found that, although not constructed for water quality treatment, the vegetated medians and shoulders consistently reduced the concentrations of suspended solids and the metals copper, lead, and zinc (see table 13-3). The results for Moreno Valley were attributed to insignificant vegetation coverage at only 25%. However, the study found no change for nitrogen and phosphorus concentrations following infiltration. Site variations in slope, climate, vegetation coverage, soil characteristics caused varying minimum effective widths, from 4.2 to 13m, to produce constant discharge. Given a minimum effective width, the vegetation species and height did not affect performance, although performance decreased rapidly for those buffers with less than 80% vegetation cover.

Table 13-3 - Total Load Reduction (%) by Vegetated Buffers at Minimum Effective Width

	TSS*	Copper	Lead	Zinc
Redding	97	76	84	90
Sacramento	85	83	87	87
Camp Pendleton	77	88	83	92
San Rafael	96	98	98	97
Cottonwood	96	95	95	97
Irvine	97	98	99	99
Yorba Linda	94	96	95	98
Moreno Valley	-450	46	-63	68

* total suspended solids
source: Barrett et al. 2005

IV. Porous Asphalt and Permeable Pavers

Figure 13-3 - permeable paving

As with vegetated swales, porous asphalt and concrete can also successfully remove pollutants from stormwater prior to infiltration[11]. A study on the pollutant removal capacity of porous asphalt in Rezé, France[12], compared runoff at the outlets of a porous asphalt road with reservoir structure and of a nearby reference catchment, an impervious roadway. Built in 1991, samples were collected after rain events for 8 years. The study found that metallic pollutants were mainly retained within the porous asphalt structure itself, with minimal contaminants entering the soil under the structure. The porous asphalt road achieved mean reductions of 59% for suspended solids, 84% for lead, 73% for zinc, and 77% for cadmium compared to the surface runoff. A similar study in Nottingham, England[13] found that a parking lot surfaced with open-celled concrete grids with aggregate fill successfully trapped most suspended solids and metals.

Webb (2006)[14] reviewed several studies on interlocking permeable concrete pavement systems, and found high success rates for stormwater treatment capabilities. One study found that such pavement systems with gravel, basalt, or limestone base materials provided 88-98% removal of lead, cadmium, copper, and zinc; an examination of the paver installation 15 years after its construction revealed no significant concentrations of heavy metals and elevated but still low concentrations of mineral oil in the underlying soils. He concludes that, for areas with typical driving surface pollutants and pollutant concentrations, and with appropriate

Table 13-4 - Water quality results for pollutant removal by permeable paving

Mean concentrations of detected constituents from storm samples in 2001–2002 (1996 results from Booth and Leavitt [22] in square brackets). Nine storms sampled in 2001–2002; three in 1996

	Hardness (mg $CaCO_3$/l)	Conductivity (μmhos/cm)	Copper (μg/l)	Zinc (μg/l)	Motor oil (mg/l)
Infiltration samples					
Gravelpave^{2}®	22.6	47	0.89 (66% <MDL)	8.23 (22% <MDL)	<MDL
	[20.3]	[63]	[1.9 (67% <MDL)]	[2.0 (67% <MDL)]	
Grasspave^{2}®	14.6	38	<MDL	13.2	<MDL
	[22.8]	[94]	[21.4 (33% <MDL)]	[2.5 (67% <MDL)]	
Turfstone®	47.6	114	1.33 (44% <MDL)	7.7 (33% <MDL)	<MDL
	[49.4]	[111]	[1.4 (67% <MDL)]	[<MDL]	
Uni Eco-Stone®	49.5	114	0.86 (77% <MDL)	6.8 (33% <MDL)	<MDL
	[23.0]	[44]	[14.3 (33% <MDL)]	[7.9 (33% <MDL)]	
Surface runoff samples					
Asphalt	7.2	13.4	7.98	21.6	0.164 (11% <MDL)
	[6.1]	[17.0]	[9.0 (33%<MDL)]	[12]	

In parenthesis is the percent of samples that fell below detectable levels. Lead was not detected in 2001–2002 but was present in 5 of 15 samples in 1996; motor oil was not tested in 1996. <MDL = all samples below minimum detection limit. Minimum detection limits listed in text.

source: Brattebo and Booth 2003

underlying soils[15], pervious cement concrete pavement can "adequately protect groundwater by providing stormwater treatment within the pavement section for target pollutants" (p. 3).

Positive results were also found for a study that examined four manufactured permeable paver systems in parking areas for durability, ability to infiltrate runoff, and the chemical quality of runoff being reintroduced to groundwater[16,17]. Four permeable paving systems, each consisting of a matrix of concrete blocks or plastic grids and voids filled with sand, gravel, or soil, were installed in an employee parking lot in Renton, Washington in 1996. These systems were Grasspave^{2}®, Gravelpave^{2}®, Turfstone®, and UNI Eco-Stone®. The lot covered deep, well-drained soil and had high vehicle occupancy five days a week throughout the study. Each paving system was installed in two parking stalls, with a ninth asphalt stall to serve as a control, and were underlain by a series of gutters and pipes to collect surface runoff and subsurface infiltrate. Water samples were collected after rainfall events in 1996 and again in 2001-2002 and were analyzed for hardness, conductivity, diesel fuel, motor oil, and dissolved lead, copper, and zinc.

The quality of the infiltrated stormwater was generally much higher than the asphalt runoff (see table 13-4). The results shown in this table can be read as follows: for example, water samples infiltrated through Gravelpave^{2}® had a mean copper concentration of 0.89μg/L, while the samples collected from asphalt runoff had a mean copper concentration of 7.98μg/L. These numbers indicate that the Gravelpave^{2}® reduced the concentration of copper in the runoff by nearly 90%. Furthermore, 67% of the 1996 samples filtered by Gravelpave^{2}® had quantities of copper too low to detect, while only 33% of the unfiltered 1996 samples had quantities of copper too low to detect.

The initial results of this study in 1996 showed undetectable levels of diesel fuel and motor oil and low levels of lead, copper, and zinc in the infiltrate from all paving systems. Results following five additional years of constant use showed that the paving systems and underlying soils were still successfully filtering contaminants from stormwater. For copper and zinc, toxic concentrations were reached in 97% of the asphalt runoff samples, while most infiltrated stormwater samples had concentrations below detectable levels. Motor oil was much lower in the infiltrate than in the surface runoff, and conductivity and hardness were relatively constant. Neither lead nor diesel fuel were detected in any sample, runoff or infiltrate.

How do these permeable pavements continue to remove pollutants from stormwater over time? Porous pavements actually destroy oil pollutants through the biochemical activity of bacteria and fungi that use the pavement as a substrate[18]. The oils are broken down and disperse safely into the atmosphere as carbon dioxide and water; studies have shown that 97-99% of applied motor oil is trapped in porous pavements and biodegraded[19,20]. As for other pollutants, while the results of the Renton, Washington study indicated that water-quality performance diminishes over time for permeable paving systems, it is unlikely to be problematic. For this study, water had travelled less than 10cm through the soil before being sampled as infiltrate; the authors noted that the longer flow paths to groundwater tables in the field would most likely lead to even greater uptake of pollutants and a decrease in the potential for groundwater contamination. They concluded that, given favourable soil conditions and climatic effects similar to those of the Pacific Northwest, such as the low rainfall intensities, little road salt application, and lack of extended periods of sub-freezing weather, permeable paving systems can substantially improve the quality of urban stormwater runoff prior to its reintroduction to groundwater sources. Even where porous pavement had been infiltrating stormwater for 20 years, stormwater contaminants were still found to be accumulating in the uppermost 5cm of soil underneath the paving structure[21]. Nearly all types of subgrade soils under porous pavements are effective in protecting groundwater quality, with the exception of rapidly draining soils[22].

Finally, while there has been concern that the accumulation of heavy metals and other pollutants in the filtering soils and plant materials of swales, buffers, and underlying materials of permeable pavement could eventually cause the material to be classified as hazardous waste, Barrett et al.[23] found that this is unlikely to be a problem. Their study of vegetated buffer strips along highways found pollutant concentrations in soil samples taken at the end of the two-year study to be low (see table 13-5); for example, the average concentration of lead was 45.6 µg/L, while the hazardous waste threshold for lead is 5,000µg/L. Since average stormwater runoff contains low pollutant concentrations, even after years of runoff treatment the soil concentrations would be low enough that the removal or disposal of these soils would not have special requirements.

Table 13-5 - Roadside Soil Pollutant Concentration Following Two Years of Stormwater Filtration

Constituent	Average Concentration (µg/L)	Maximum Concentration (µg/L)	Hazardous Waste Threshold (µg/L)
Arsenic	2.2	4.7	5000
Cadmium	0.5	0.5	1000
Chromium	8.2	19.0	5000
Copper	24.5	210.0	25000
Nickel	8.4	31.0	20000
Lead	45.6	240.0	5000
Zinc	44.5	120.0	250000

source: Barrett et al. 2005

V. Conclusion

Bioretention swales, vegetated buffers, and permeable paving can all be effective means for removing most residential-source stormwater pollutants and preventing their entry into groundwater sources. Since the success of the removal of stormwater pollutants by shallow infiltration devices depends in varying degrees on the sedimentation and filtration properties of soil, soil depth and texture, and toxin mobility, surface infiltration systems should be designed to respond to site-specific conditions, such as soil type, pollutant concentrations, climate, slope, and vegetation. Most stormwater pollutants are more mobile in water than in soil, making the potential for groundwater contamination much higher when this water is injected subsurface; when designed appropriately, shallow surface infiltration systems are particularly effective at removing heavy metals and organic compounds, and are far superior to the method of subsurface injection which often introduces these contaminants directly into groundwater supplies without the benefit of soil infiltration.

Notes

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[2] Environmental Protection Agency (EPA). 1993. Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters.

[3] Pitt, R., S. Clark, and K. Parmer. 1994. Potential groundwater contamination from intentional and nonintentional stormwater infiltration. Cooperative Agreement No. CR819573 EPA/600/SR-94/051. Storm and Combined Sewer Pollution Control Program US. Cincinnati: Environmental Protection Agency.

[4] Pitt, R. 2000.

[5] Pitt, R., S. Clark, and K. Parmer. 1994.

[6] De-icers are not commonly applied in most areas of the Pacific Northwest, and these areas do not exhibit general salinity of surface water and groundwater systems.

[7] Barrett, M., A. Lantin, and S. Austrheim-Smith. 2005. Stormwater pollutant removal in roadside vegetated buffer strips. Conference paper presented at the 2005 World Water and Environmental Resources Congress, May 15-19, 2005, Anchorage, Alaska. American Society of Civil Engineers.

[8] Davis, A. P. et al. 2001. Laboratory Study of Biological Retention (Bioretention) for Urban Storm Water Management. *Water Environ. Res., 73(1)*, 5-14.

[9] Davis, A. P. et al. 2003. Water Quality Improvement through Bioretention: Lead, Copper, and Zinc. *Water Environ. Res., 75(1), 73-82*.

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[15] Appropriate underlying soils were identified to be a) a water quality filter course, typically 1" thick coarse sand, or b) minimum 18" depth of soil with a long-term infiltration rate of <2.4 in./hr. and a cation exchange capacity of ≥ 5 milliequivalents/100 grams of dry soil.

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[22] Pitt, R. 2000.

[23] Barrett, M., A. Lantin, and S. Austrheim-Smith. 2005.

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